DESIGN OF A MULTIVARIABLE INTEGRATED CONTROL FOR A SUPERSONIC PROPULSION SYSTEM

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SUMMARY

A study was conducted of an inlet/engine/nozzle integrated control mode for the propulsion system of an advanced supersonic commercial aircraft. This study showed that integration of these control functions can result in both operational and performance benefits for the propulsion system. For example, this integrated control mode may make it possible to minimize the use of inlet bypass doors for shock position control. This may be of benefit to the aircraft as a result of minimizing: (1) bypass bleed drag effects; (2) perturbations to the aircraft resulting from the side thrust effect of the bypass bleeds; and, (3) potential unstarts of the inlet. A conceptual integrated control mode was developed which makes use of many cross-coupling paths between inlet and engine control variables and inlet and engine sensed variables. A multivariable control design technique based upon Linear Quadratic Regulator (LQR) theory was applied to designing the feedback gains for this control to allow a simulation evaluation of the benefits of the integrated control mode.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) is engaged in studies and advanced technology programs for future supersonic commercial aircraft, with emphasis on improving environmental and performance characteristics. As part of this overall program, Pratt & Whitney Aircraft (P&WA) is conducting advanced propulsion technology programs.

The time frame for these programs is consistent with advanced technology projections that would permit a U.S. entry into the commercial supersonic aircraft market by the late 1980's or early 1990's.

The work presented in this paper was accomplished during a brief study as part of a NASA-sponsored study conducted by the Lockheed-California Company, with P&WA Commercial Products Division as sub-contractor.[1]

VARIABLE STREAM CONTROL ENGINE

Results from broad parametric studies and refined integration studies indicate that the Variable Stream Control Engine (VSCE) has the greatest potential for future supersonic transports.[2,3] This VSCE concept employs variable components and a unique throttle schedule for independent control of two flow streams to provide reduced jet noise at take-off and high performance at both subsonic and supersonic cruise. Figure 1 shows the basic arrangement of the major engine components in a twin spool configuration similar to a conventional turbofan engine. The low spool consists of an advanced technology, multi-stage, variable geometry fan and a low pressure turbine. A variable geometry compressor driven by an advanced single-stage high temperature turbine makes up the high spool. The primary burner and the duct burner require low emissions, high efficiency combustors. A two stream, concentric, annular (co-annular) nozzle design with variable throat areas in both streams and an ejector/reverser make up the exhaust system.

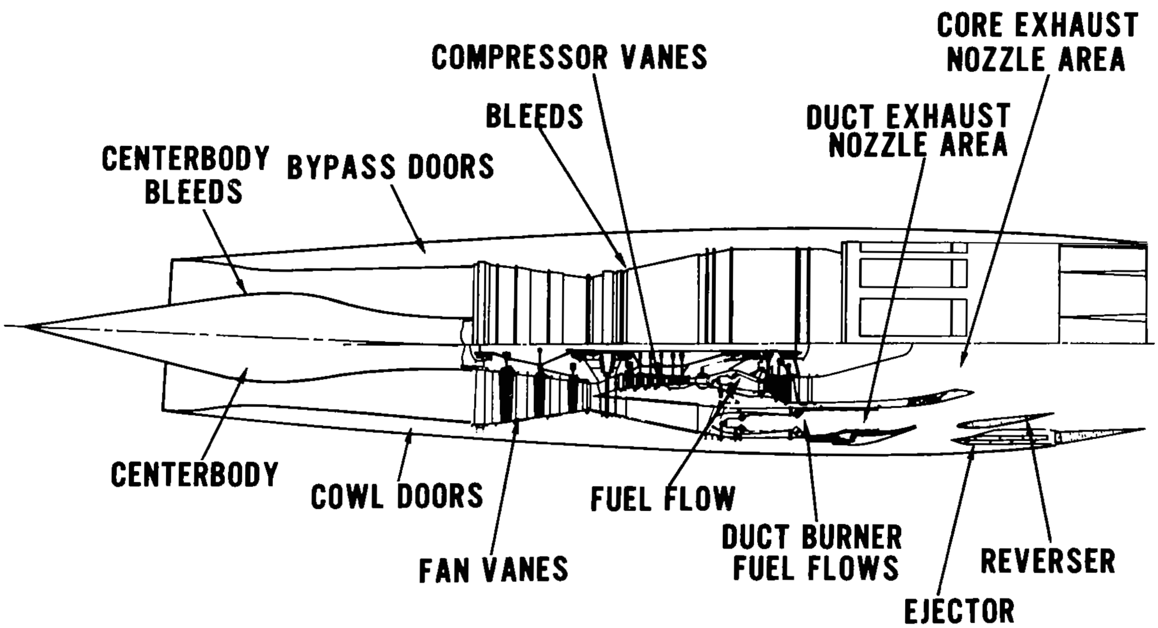

Figure 1 Propulsion System, Incorporating a Variable Stream Control Engine (VSCE), for an Advanced Supersonic.

Supersonic Inlet

The supersonic inlet for the VSCE will be either an axisymmetric configuration with a translating or collapsible centerbody, or a two-dimensional design with variable walls. Auxiliary inlet doors and bypass doors are included to satisfy off-design and transient operating conditions. During supersonic operation, the primary control requirement for the inlet is to fix the shock position at a location downstream of the throat. Varying the internal geometry, such as translating the centerbody position, varying the bypass doors and matching the engine airflow with the inlet flow rate requires coordination. This will allow optimum positioning of the shock for maximum pressure recovery while minimizing inlet spillage and bypass flow and preventing instability such as unstart and buzz.

Engine

Modulating engine airflow to match inlet airflow is important for optimizing installed performance. Selected rating parameters, such as rotor speeds and/or engine pressure ratio, are programmed into the control system to provide the specific thrust, airflow, and temperature ratings at critical operating conditions that result in the desired performance and environmental benefits.

The VSCE fan incorporates variable camber inlet and exit guide vanes. The compressor has several rows of variable stators. Accurate control of these variable geometry components is required to optimize performance over the flight envelope while maintaining stability margins.

The advanced main burner and duct burner have staged combustion systems which require accurate and independent control of fuel flow to each stage to obtain the efficiency and emissions benefits associated with these burner designs. The control system must also provide smooth light-off, stage-to-stage transfer during transient operation, and modulated total fuel flow in each burner stage to obtain the desired power settings.

Nozzle/Reverser

Continuous and independent modulation of both the primary and duct stream nozzle areas is required in conjunction with the engine control variables to provide the desired engine and nozzle operating characteristics. Control of the actuated ejector doors and the thrust reverser must also be provided.

INTEGRATION

Operation and performance of the VSCE propulsion system is a function of the interactions between the inlet, engine, and nozzle. Basic interaction effects are represented in figure 2, and individual performance factors for the inlet, engine, and nozzle are shown in figure 3. Since the integrated propulsion system is affected by all of these interactions and performance factors, it is apparent that an integrated control system is required not only to optimize individual component performance, but also to trade between engine components.

An integrated control can allow closer operation to compressor surge limits to improve compressor efficiency and pressure ratio during steady state operation, and utilize reset logic to accommodate inlet distortion effects or engine transients. Another integration approach is to use engine variables to control the inlet shock position, and thereby minimize the use of drag-inducing bypass doors.

Integration must also be provided between all four propulsion systems and between the aircraft control system. This is required to provide optimum overall aircraft performance and to provide operational reliability and safety by minimizing the possibility of inlet unstarts as a result of aircraft maneuvers. In addition, if an inlet should unstart, the impact on aircraft controllability would be minimized. Therefore, a control system is required which not only provides the propulsion system control function, but can also provide these integration functions.

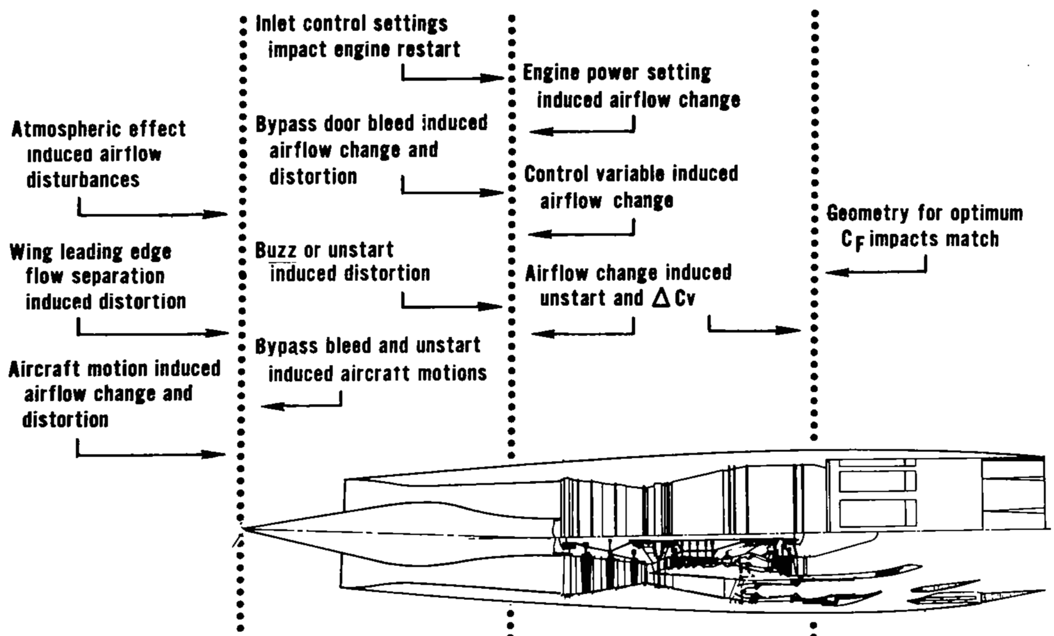

Figure 2 Propulsion System Interactions

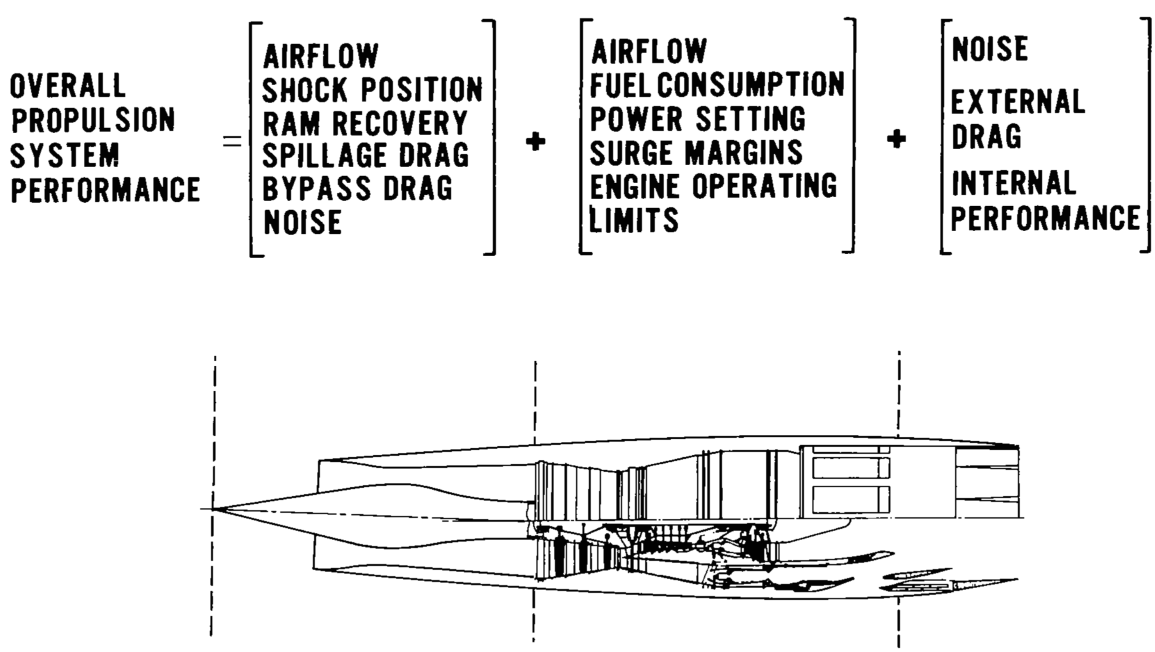

Figure 3 Propulsion System Performance Factors

Integration benefits and inlet/engine/nozzle control function integration approaches were evaluated under the conceptual integrated control study,(1) discussed previously. The integration benefits identified in this study are summarized in table 1.

TABLE I - CONTROL INTEGRATION BENEFITS

- Maximize steady state and transient performance
- Minimize inlet unstarts and engine surge during maneuvers
- Minimize occurrence of buzz
- Minimize use of drag-inducing inlet bypass doors
- Improve aircraft handling qualities
- Maximize operational safety

INTEGRATED CONTROL MODE

Given the individual control requirements for the inlet and VSCE, and integration requirements and approaches, a conceptual integrated control mode was developed. The resulting control mode, shown in block diagram form in figure 4, represents a fully integrated mode in that all anticipated significant cross-coupling loops, both within the engine and between engine and inlet, have been included. Full authority integrators were selected for main burner fuel flow (WFE), compressor bleeds, and bypass doors. Trim integrators, whose output add to steady state reference or correlation schedules, were selected for fan inlet guide vane (FIGVA), compressor stator vanes (CSVA), core nozzle area (AJE), and duct nozzle area (AJD). The use of integrators on each control variable was selected to provide accurate control to the desired propulsion system ratings.

Design and evaluation of control loop gains and dynamic compensation for such a control mode required development of a dynamic simulation of the VSCE engine and the supersonic inlet. The engine simulation consisted of detailed nonlinear dynamic representations of each engine component available from P&WA's simulation system. The inlet simulation selected was based upon a simulation technique developed at the NASA Lewis Research Center, as described in Reference 4. This simulation technique is based upon a linearized mathematical analysis of inlet dynamics and, as such, in only valid for small transient perturbations about the operating point. However, this limitation is acceptable for analysis of integrated control response since (1) engine operation at supersonic conditions is limited to a fairly linear range and, (2) it is desirable to maintain accurate control of shock position (i.e., only allow small variations from the desired shock position) so that inlet operation will also be limited to a fairly linear range.

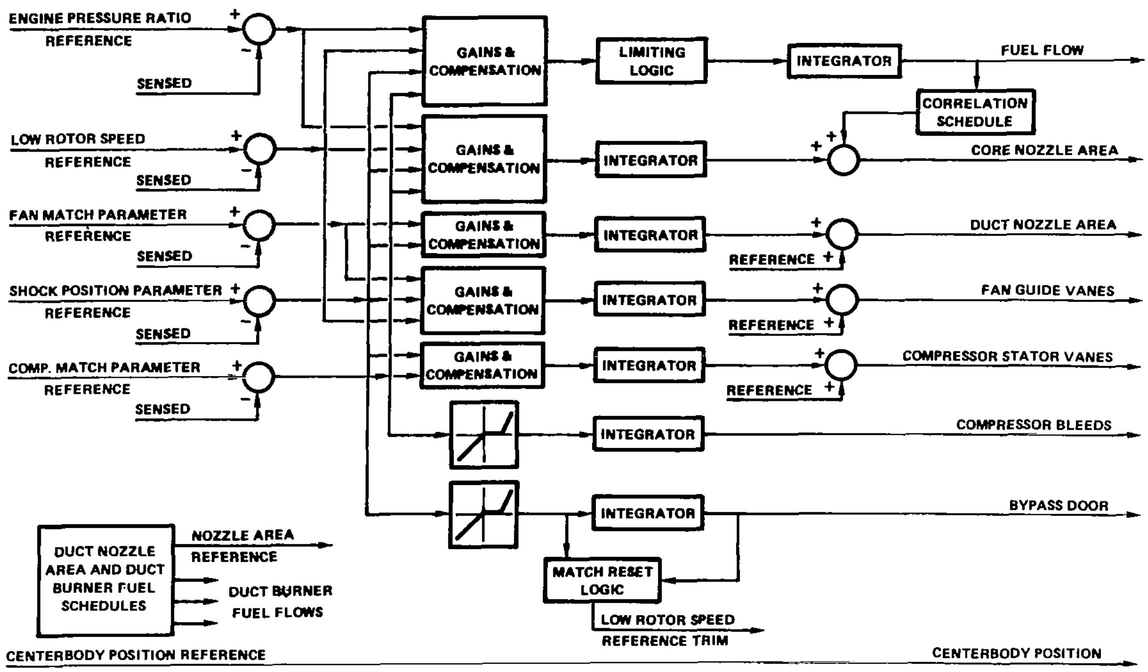

Figure 4 Conceptual Integrated Control Mode

A schematic of an ideal mixed-compression inlet is shown in figure 5. The cross-sectional area variation of the inlet is approximated by constant area sections to minimize the complexity of the resulting simulation. For each duct section chosen, the constant area approximation and a linear analysis of the compressible flow equations result in one-dimensional wave equations representing that section. These wave equations are used to represent both the supersonic and subsonic flow regions. The supersonic and subsonic flow sections are then coupled by linearized equations which relate normal shock, position to adjacent parameters. A linearized equation is also developed for bypass flow, assuming choked flow through the bypass door. Finally the linearized inlet simulation is mated with the nonlinear engine simulation to provide the exit conditions of the inlet.

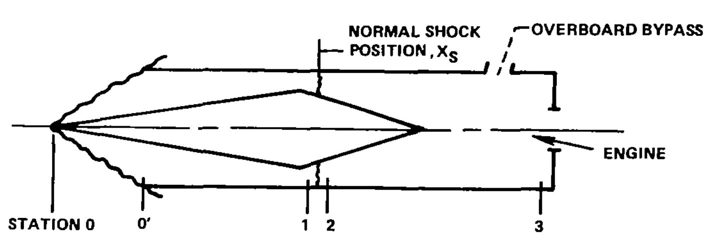

Figure 5 Idealized Mixed Compression Inlet

INTEGRATED CONTROL DESIGN APPROACH

A multivariable control design technique, based on Linear Quadratic Regulator (LQR) theory, was applied to the design of the integrated control mode for the inlet/engine. This technique provides a systematic procedure for designing all cross-coupled loops that are employed in an integrated control mode and assures advantageous use of these cross-coupling effects. Since the LQR multivariable control design technique is a linear technique, the nonlinear equations representing the engine must be linearized and combined with the linear equations representing the inlet. Accomplishing this required definition of the state, control and output variables for the engine and inlet. Generally, it is not desirable to include every state variable in the engine since this can result in an unnecessarily complex control system; i.e., the LQR technique determines control feedback gains from every state variable selected to represent the system. A more effective approach is to recognize the frequency range over which active control is really desired, or possible, and simplify the state variable representation to include only those states associated with engine dynamics in this frequency range.

Based on such considerations, the state, control and output variables shown in table II were selected for the inlet/ engine representation. Even

TABLE II - STATE, CONTROL, AND OUTPUT VARIABLES

X - STATE VARIABLES	U - CONTROL VARIABLES	Y - OUTPUT VARIABLES
X1 - LOW ROTOR SPEED	U1 - MAIN BURNER FUEL FLOW	Y1 - LOW ROTOR SPEED
X2 - HIGH ROTOR SPEED	U2 - CORE EXHAUST NOZZLE AREA	Y2 - HIGH ROTOR SPEED
X3 - MAIN BURNER PRESS.	U3 - DUCT EXHAUST NOZZLE AREA	Y3 - ENGINE PRESS. RATIO
X4 - CORE STREAM EXHAUST PRESS.	U4 - COMPRESSOR STATOR VANES	Y4 - NORMAL SHOCK POSITION
X5 - DUCT STREAM PRESS.	U5 - FAN STATOR VANES	Y5 - FAN PRESS. RATIO
X6 - NORMAL SHOCK POSITION	U6 - INLET BYPASS DOOR AREA	Y6 - COMPRESSOR PRESS. RATIO
X7 - INLET SUBSONIC SECTION TEMP.		Y7 - INLET SUBSONIC SECTION PRESS.
X8 - INLET SUBSONIC SECTION PRESS.		Y8 - HIGH TURBINE INLET TEMP.
X9 - INLET SUBSONIC SECTION AIRFLOW		Y9 - THRUST

though all of the inlet state variables are associated with high frequency dynamics, it is necessary to include several of them since control of the shock position requires relatively high frequency response control loops. The inlet state variables associated with the supersonic flow section were eliminated since it was found that feedback of these variables did not contribute significantly to effective control action. The first six output variables were selected to be consistent with the reference variables shown in the conceptual control mode in figure 4.

Using these state, control and output variables the inlet/ engine simulation was linearized at a supersonic flight condition corresponding to an altitude of 16,800 m (55000 ft) and a Mach number of 2.3. This linearization resulted in a state variable representation of the system consisting of the following two matrix equations:

$$\delta \dot{X} = A \, \delta X + B \, \delta U$$

$$\delta Y = C \, \delta X + D \, \delta U$$

The next step in the LQR control synthesis procedure is to define a performance index as a measure of the goodness of the control effectiveness. A quadratic performance index of the following form is required for the LQR synthesis technique to solve the "output regulator" problem.

$$\text{Performance Index} = J(\delta U) = \frac{1}{2}\int_0^\infty \left[\delta Y^T Q \, \delta Y + \delta U^T R \, \delta U \right] dt$$

Minimization of this performance index results in "optimal transient performance" as determined by the selected values in the Q and R weighting matrices on the output and control variables, respectively. For example, placing a high weighting on shock position will improve control regulation of shock position. With the performance index defined, the "output regulator problem" is solved by solving the matrix Riccati equation for the steady state value of K.

$$-\dot{K} = KA + A^T K - G^T \hat{R} G + C^T Q C$$

where $\hat{R} = R + D^T Q D$

and $G = \hat{R}^{-1} (D^T Q C + B^T K)$

The matrix G is the matrix of feedback gains from each state variable to each control variable.

Referring back to figure 4, it can be seen that integrators are desired on each control variable to maintain zero errors between reference and sensed engine variables during steady state operation. Note that the reference variables for fan match, compressor match and shock position were replaced with fan pressure ratio, compressor pressure ratio and actual normal shock position for this study. These integrators were accommodated by including them as additional state variables along with the inlet/engine state variables, and solving the matrix Riccati equation for the control feedback gains from the complete set of states. This approach results in a solution for the G matrix which can be broken down into a G1 matrix for the inlet/engine states and a G2 matrix for the control integrators as shown in figure 6.

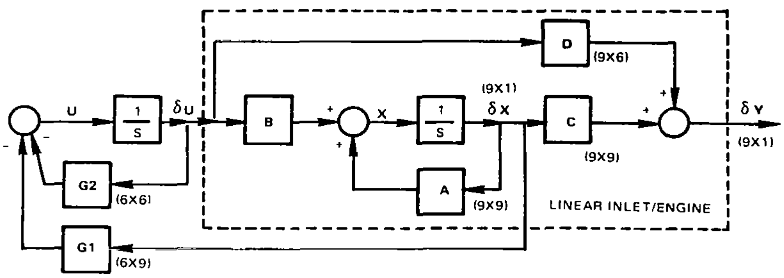

Figure 6 Solution of the Matrix Riccati Equation Determines the G1 and G2 Feedback Gain Matrices from the Inlet/Engine and Control State Variables

The resulting control mode structure is not equivalent to that shown in figure 4. To obtain this structure requires a transformation of the control gain matrices G1 and G2 to the new matrices H, L1 and L2 operating on the output variables Y. Defining the differentials δU and δY as

$$\delta U = U - Uref$$

$$\delta Y = Y - Yref$$

allows implementation of the control system, as shown in figure 7, on a nonlinear inlet/engine simulation for evaluation of small perturbation response at the selected operating point.

The L2 gain matrix is required if the number of state variables is larger than the number of control variables. This can be seen more clearly by considering the summary of the manipulations discussed above. First, the control design procedure determines a control feedback gain from every state variable to every control variable; i.e., the G matrix or the G1, and G2 matrices. Then a set of independent output or observed variables (which can be sensed), equal in number to the number of state variables, is selected to replace the state variables; i. e., the set of state variables, selected for convenience of analysis, may not all be easily measured or may not be equal to the reference variables desired for closing the integral control loops. In this integrated control mode, six reference variables are selected for driving the control integrators to obtain the desired steady state operating point. Thus, the first six output variables must be the same as the six reference variables. This in turn allows the manipulation of the control gain matrices into the structure shown in figure 7 with the L1 and H matrices acting on the first six output error terms. The L2 matrix then operates on the leftover output variables.

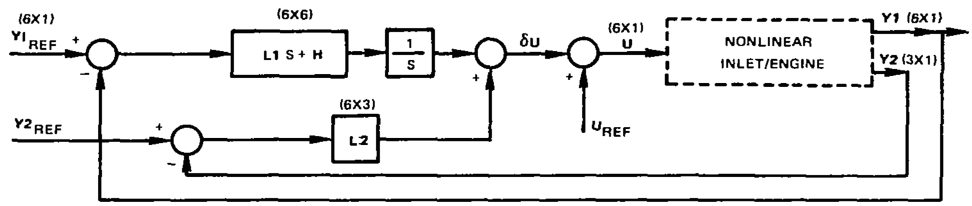

Figure 7 Transformation of the Control Mode Structure to Integral and Proportional Control Paths

If the key inlet/engine variables have been chosen for the first six closed loop control paths, then many of the remaining paths working through the L2 matrix will probably be insignificant and be able to be ignored. If all of these paths can be ignored, then the control mode structure reduces completely to that desired in figure 4. This complete process of mode structure modification and elimination of insignificant gain terms was not carried out during this brief study. A partial transformation of the gain matrices was made, as shown in figure 8, which feeds back the first six output variables for forming the integrator error terms, but retains the remainder of the feedbacks from the inlet/engine state variables. All simulation runs were then made with all elements of the gain matrices retained.

INTEGRATED CONTROL TRANSIENT PERFORMANCE

The LQR control design technique was used to define the feedback control gains, previously discussed, at the 16800 m (55000 ft) altitude, 2.3 Mach number flight condition for the fully integrated control mode. These gains were then implemented on the nonlinear inlet/engine dynamic simulation, as indicated in figure 8, to evaluate small perturbation transients about the steady state operating point. A non-integrated control mode was also designed for comparison with the integrated control mode in order to evaluate operational benefits associated with the integrated concept. This non-integrated control was developed by applying the LQR control design technique to determine the feedback control gains for the engine by itself. Then a single-input, single-output control loop was designed for the inlet to control shock position with inlet bypass doors.

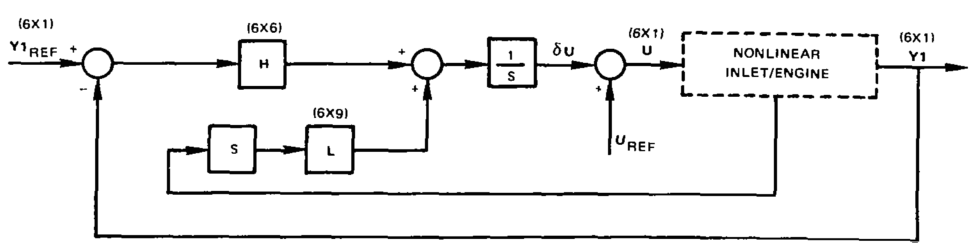

Figure 8 Partially Transformed Control Mode Structure Used for Transient Evaluations

Two types of small perturbation transients were evaluated on the dynamic simulation with the integrated and non-integrated control modes. The first consisted of a 1 percent pulse in ambient pressure of 0.04 second duration to simulate an external disturbance such as a wind gust. The second consisted of a step change in duct burner fuel flow to simulate a duct burner light-off. For this study, it was also assumed that all state variables including shock position were directly measurable.

Transient plots of shock position and inlet bypass door area for the pressure perturbation transients for both control modes are shown in figure 9. For both the integrated and non-integrated control modes the deviation in shock position towards unstart was approximately the same. The implication is that the integrated control mode is not providing any better control of shock position than the non-integrated control. In fact, the integrated control results show bypass door area moving more than in the non-integrated control case to result in the same quality of shock position control. This is theorized to result from the manner in which the engine is being controlled in both cases.

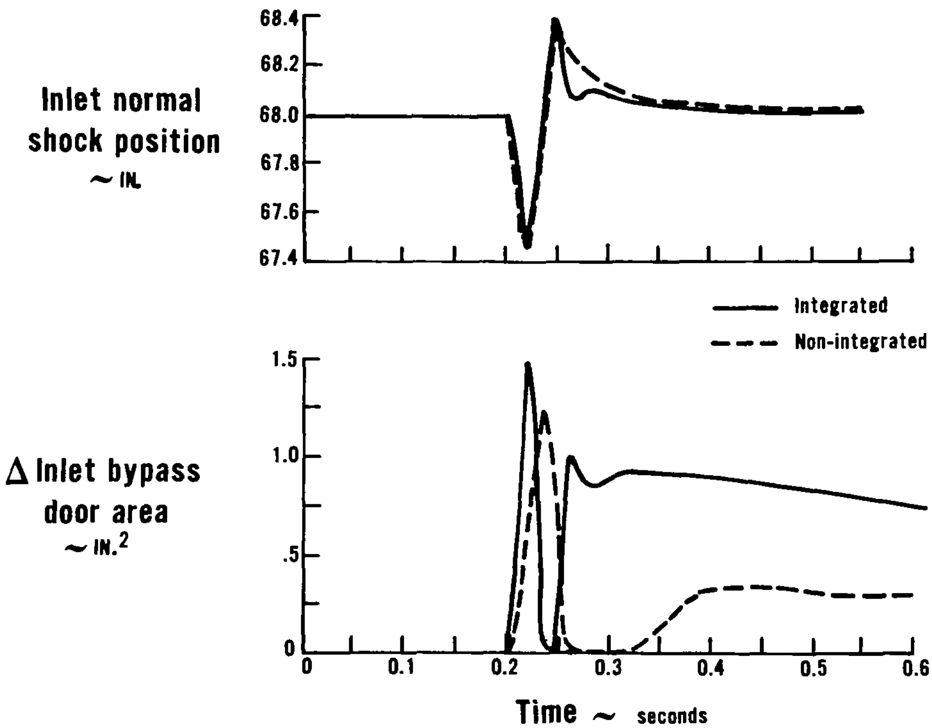

Figure 9 Transient Response to an Ambient Pressure Pulse

Referring back to figure 4, it is seen that the reference parameters for the engine, i.e., the first six output variables, are such that regulating to these variables results in accurate control of engine corrected airflow. Thus, the engine control portion of both control modes responds rapidly to changes in ambient pressure since this has an immediate effect on the engine reference variables. The result is rapid movement of engine control variables to restore corrected airflow operation. This, in turn, contributes directly to minimizing shock position movement.

The fact that the integrated control mode made more use of the bypass door area would imply that the engine control portion of the integrated mode was not as well tuned as the engine control for the non-integrated control mode. In other words, the weighting gains in the performance index would have to be changed in the design procedure for the integrated control mode to reduce its dependence on bypass doors. These iterations of the control design were not carried out during this study.

Results of the duct burner light-off transients for both control modes are shown in figure 10. The integrated control mode results in less movement of shock position with less use of bypass doors than does the non-integrated mode. These results indicate that there is a potential benefit of an integrated control mode in terms of minimizing use of the inlet bypass doors for shock position control.

To evaluate this potential benefit further would require additional analysis of both the integrated and non-integrated control modes.

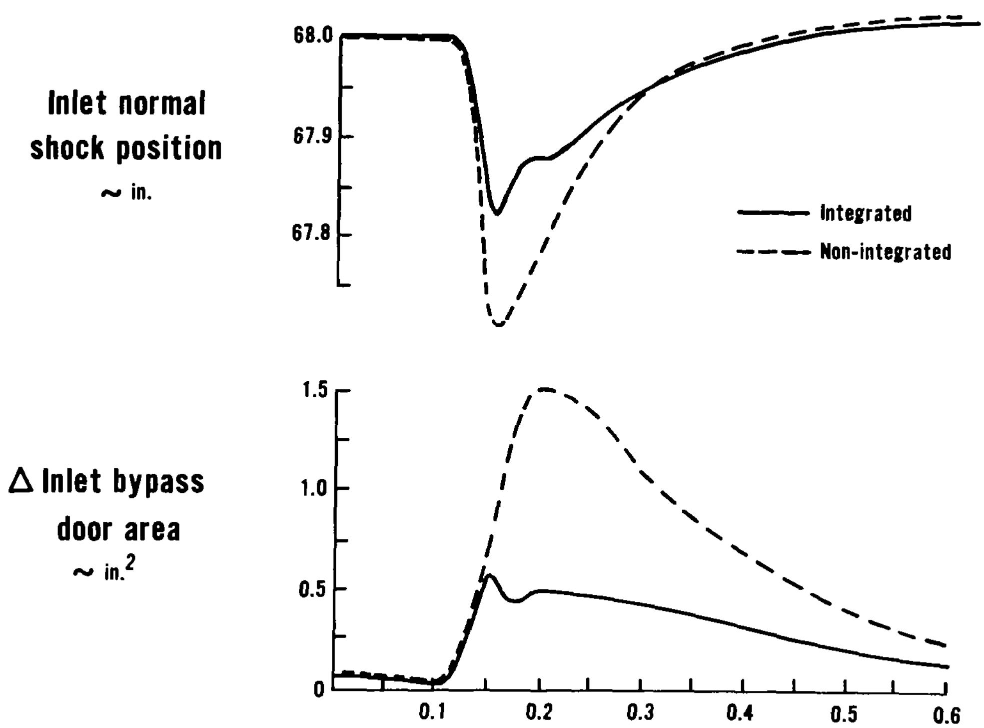

Figure 10 Transient Response to a Duct Burner Light-Off

CONCLUSIONS

The conceptual integrated control mode, for an Advanced Supersonic Transport propulsion system, evaluated in this study, makes use of several cross-coupling paths between inlet and engine control variables and inlet and engine sensed variables. Design of the control loop gains and dynamic compensation for such a control mode can be effectively accomplished utilizing a multivariable control design technique based on Linear Quadratic Regulator Theory. Such integrated control modes may provide operational and performance benefits such as minimizing the use of inlet bypass doors for shock position control.

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